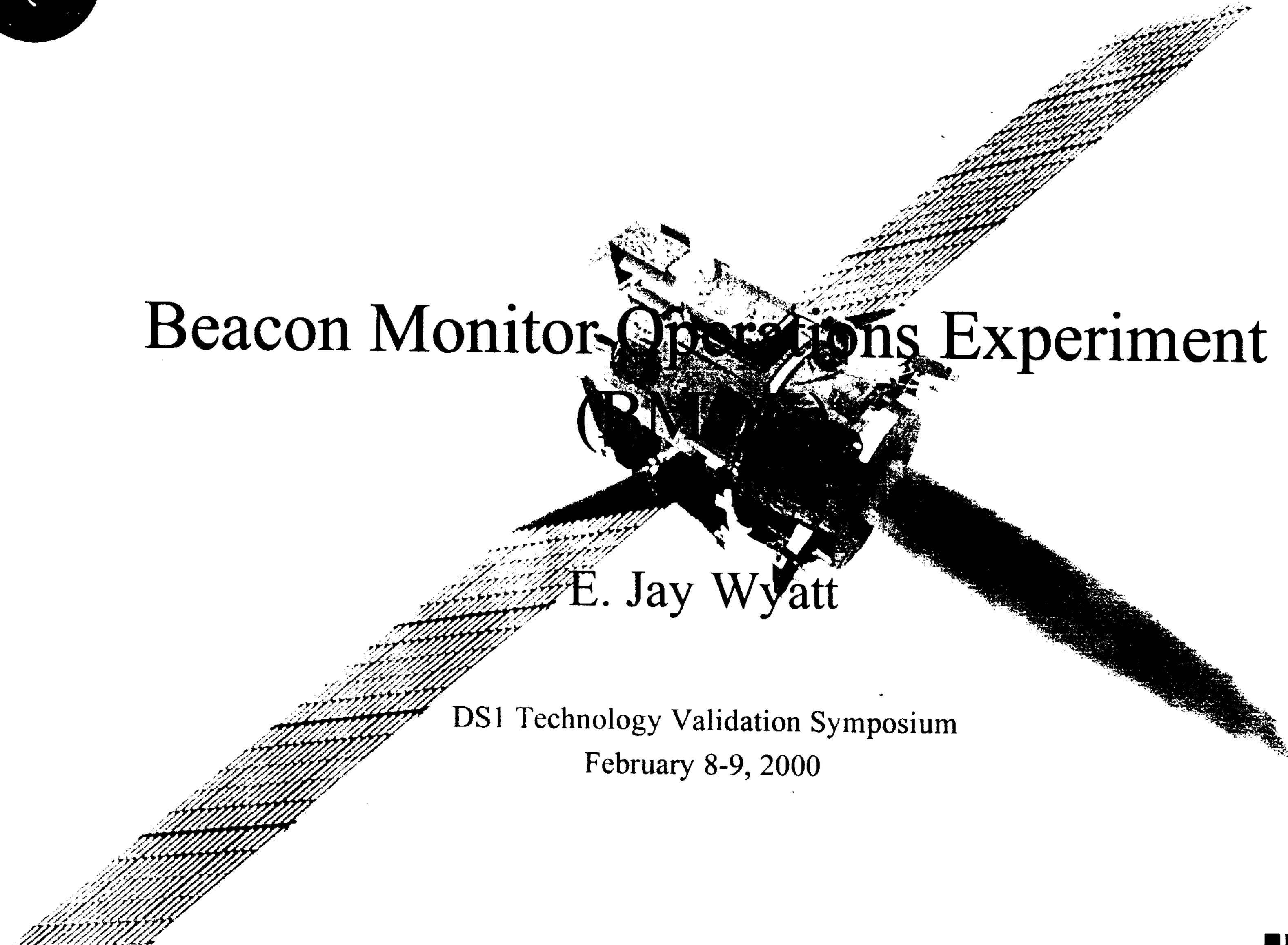


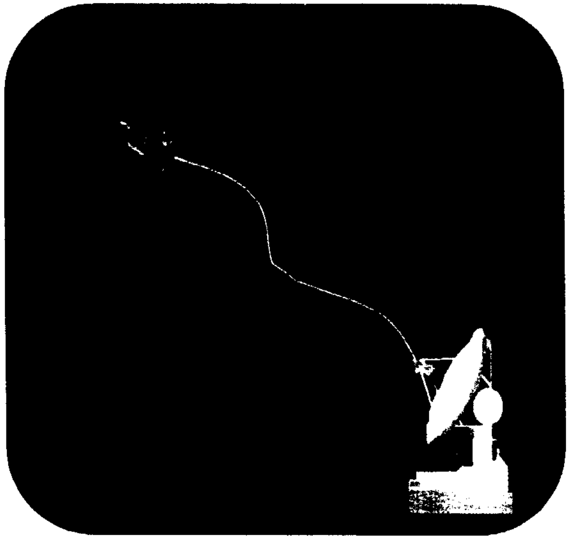
# Beacon Monitor Operations Experiment (BMOX)

E. Jay Wyatt

DS1 Technology Validation Symposium
February 8-9, 2000

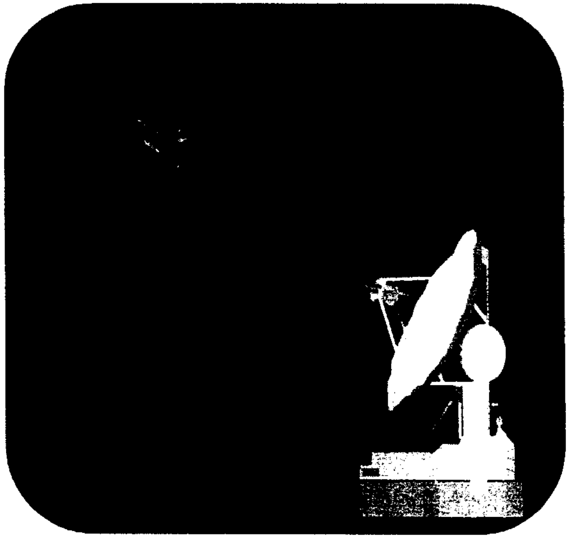
# Introduction

## Beacon Monitor Operations Technology Components



### Beacon Tone System

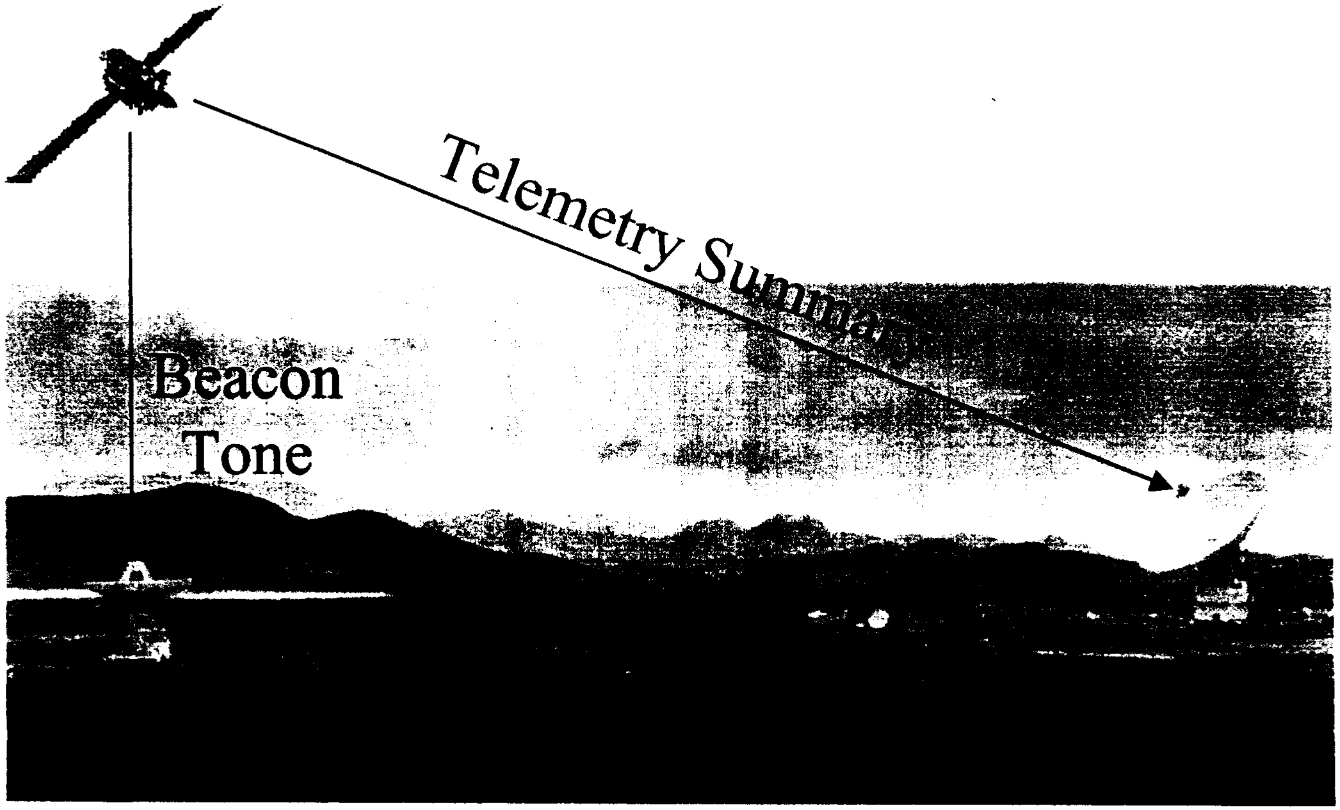
- Spacecraft initiates contact when spacecraft software indicates that ground intervention is required
- Otherwise, beacon tones indicate that the spacecraft is functioning normally



### Onboard Data Summarization

- Spacecraft sends summarized telemetry when the ground responds to the beacon tone signal

# Operational Concept



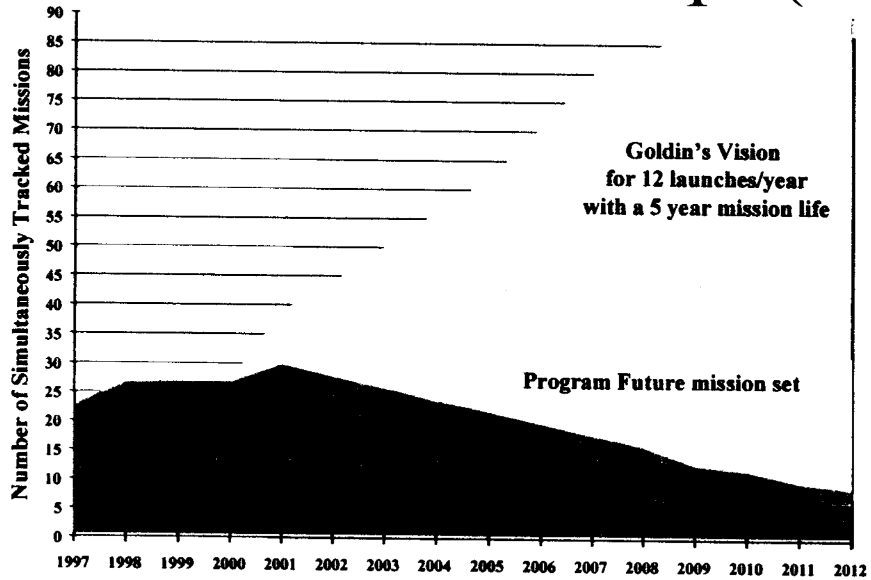

Pager Notification → Schedule Telemetry Track → Analyze Summary Data

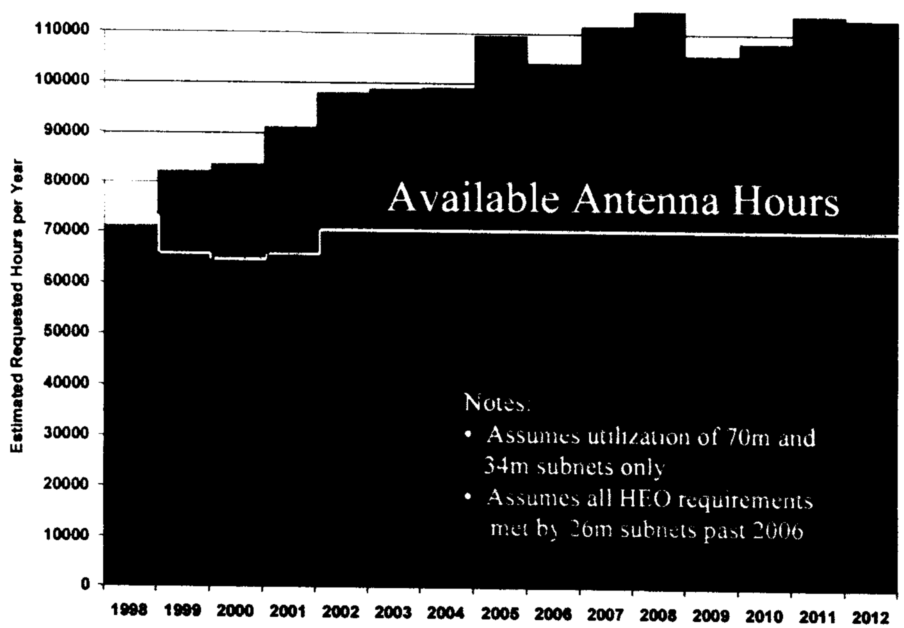
# This presentation will cover:

- Technology Overview
- Deep Space One Experiment Overview
- Experiment Results
- Future Work

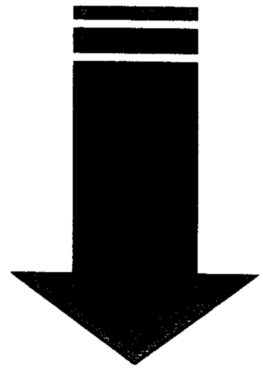
The research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

# Origins of the Concept (DSN Perspective)



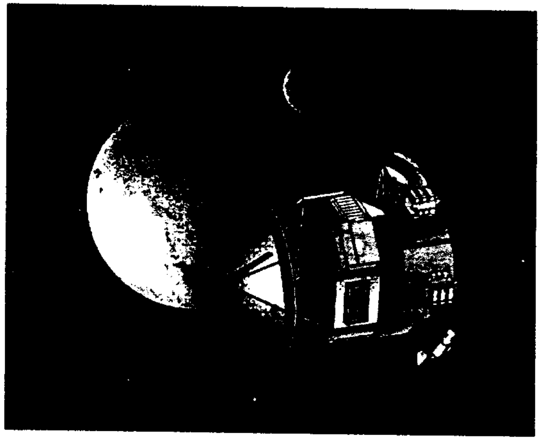




NASA's vision for darkening the skies with small autonomous spacecraft by early in the next century



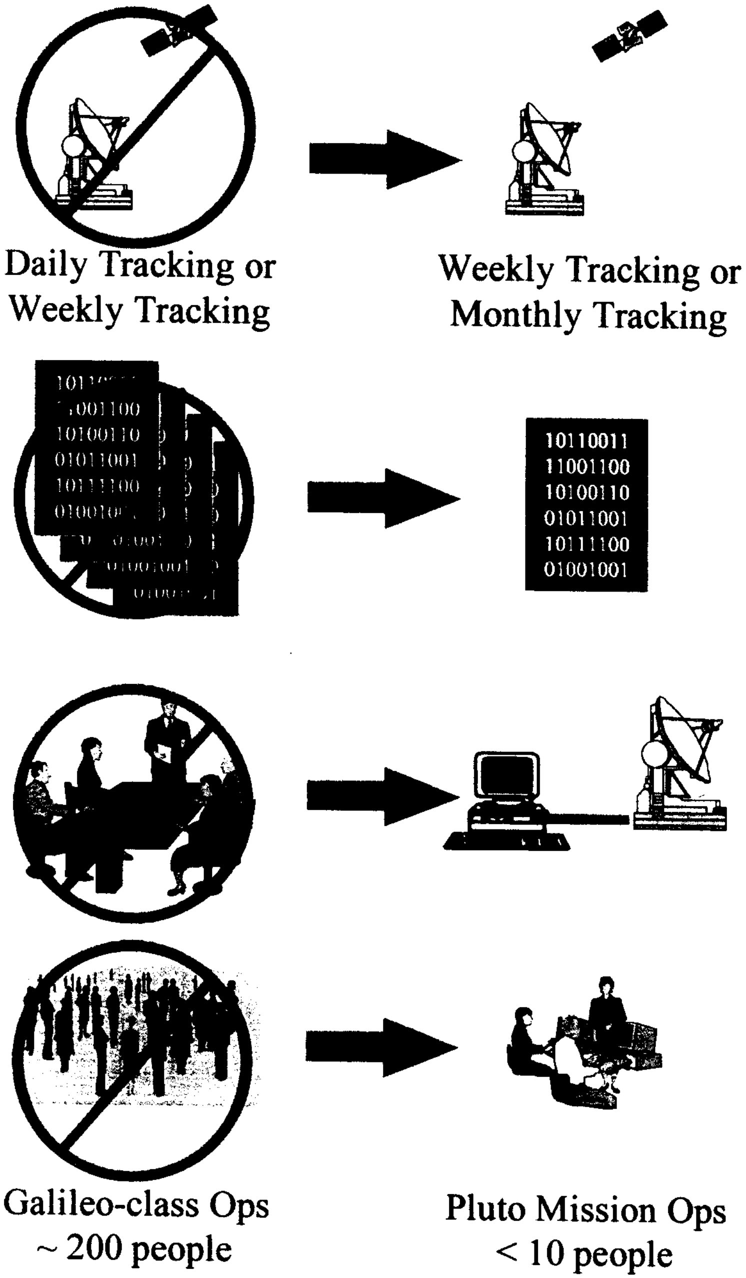
Results in severe oversubscription of DSN antenna resources. Beacon technology can reduce mission tracking requirements.

# Origins of the Concept (Mission Perspective)



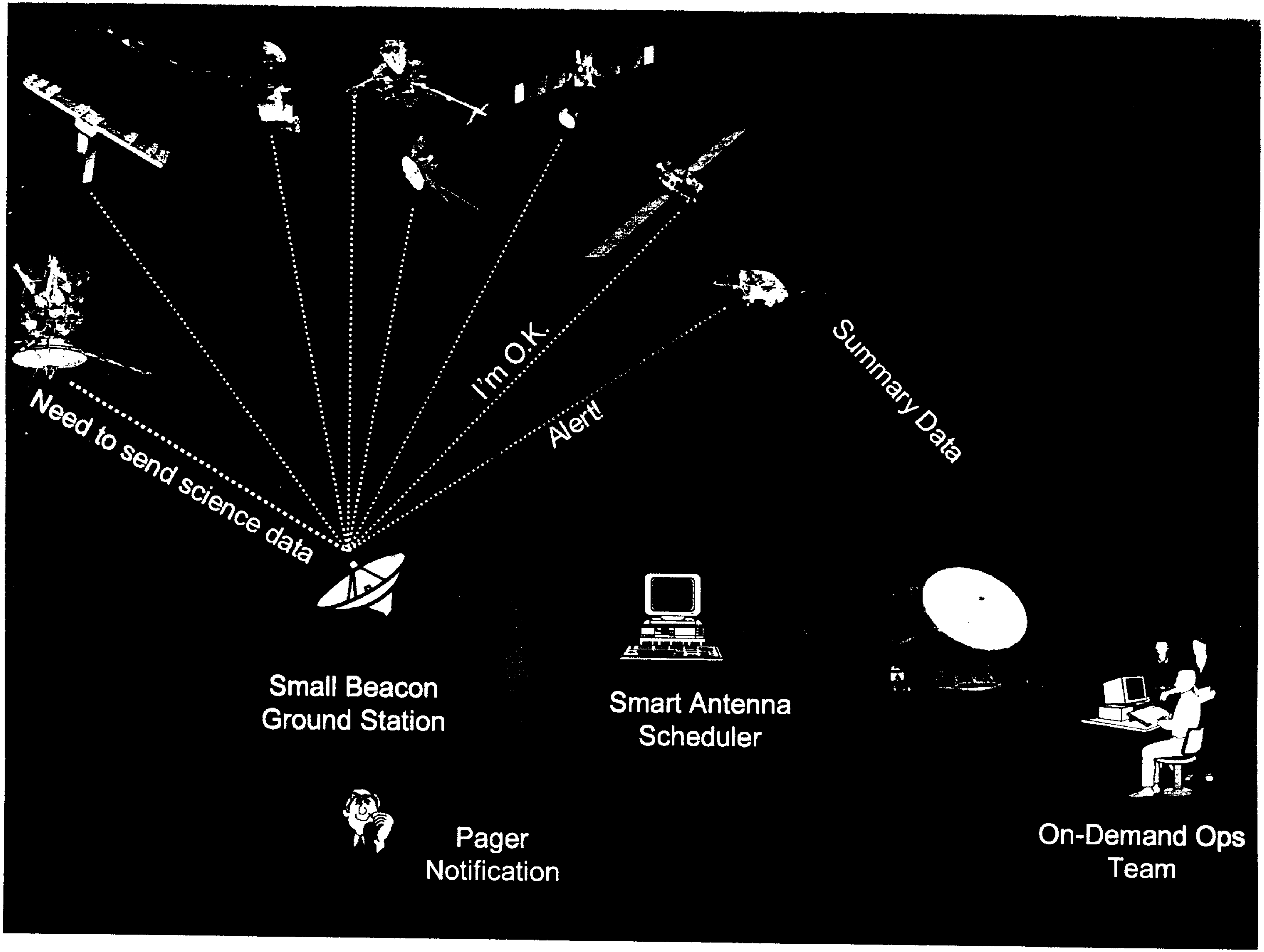
- NASA Mission Environment
  - Slim operations budgets
  - Transition towards full-cost accounting
  - Changes in mission risk policies
- Originally conceived for NASA's planned missions to Pluto and Europa
  - Highest payoff is to reduce the amount of tracking and decrease the operations team size
  - Need operations concepts that are flexible
    - to accommodate spacecraft operability constraints
    - to enable gradual scale-back in personnel support
    - to enable migration of functions to the spacecraft as the mission progresses
    - because it is hard to anticipate minimum monitoring requirements pre-launch

# Technology Objectives




- Reduce frequency telemetry tracking during routine mission phases
- Reduce the amount of telemetry when tracking is required
- Provide rationale for automated antenna scheduling solutions for the Deep Space Network
- Investigate innovative staffing solutions for shared and on-demand operations teams

# Future Vision

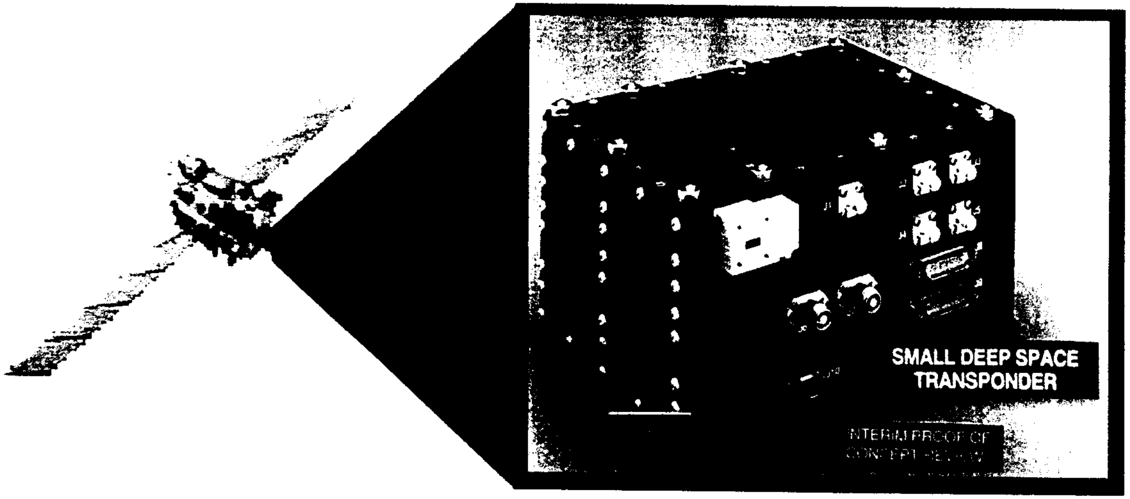


# Tone System: Selection

- Missions determine the mapping of s/c state to urgency of ground response
- Tones cannot transition to a lower state unless reset by ground command

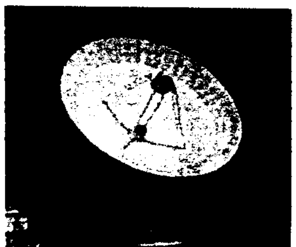
| | |
|---|---|
| | All functions are performing as expected. No need to downlink engineering telemetry. |
| INTERESTING | Establish communication with the ground when convenient to obtain data relating to an event.<br>Examples: device reset due to SEU |
| IMPORTANT | Spacecraft needs servicing within a certain time or spacecraft state could deteriorate or critical data could be lost.<br>Examples: solid state memory near full, non-critical hardware failure |
| URGENT | Spacecraft emergency. A critical component has failed. The spacecraft cannot adequately recover. Ground intervention is required immediately. On DS1, set by Fault Protection after entering "standby" mode. |
| *No Tone* | Beacon mode is not operating, telecom is not earth-pointed, or a spacecraft anomaly prohibited tone from being sent. |

# Tone System: Overview




## Small Deep Space Transponder

- Can generate 32 X-band tones to for 8 s/c in one antenna beamwidth
- Precursor to the Space Transponding Modem (STM) which also supports beacon signaling



## DS1 Tone Detection at DSS13

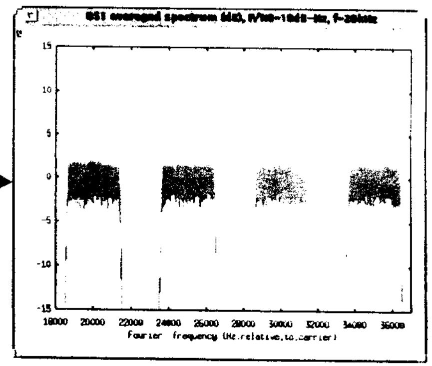
- Tones can utilize smaller aperture antennas
- Detection time is short (5-25 minutes)

LNA & D/C

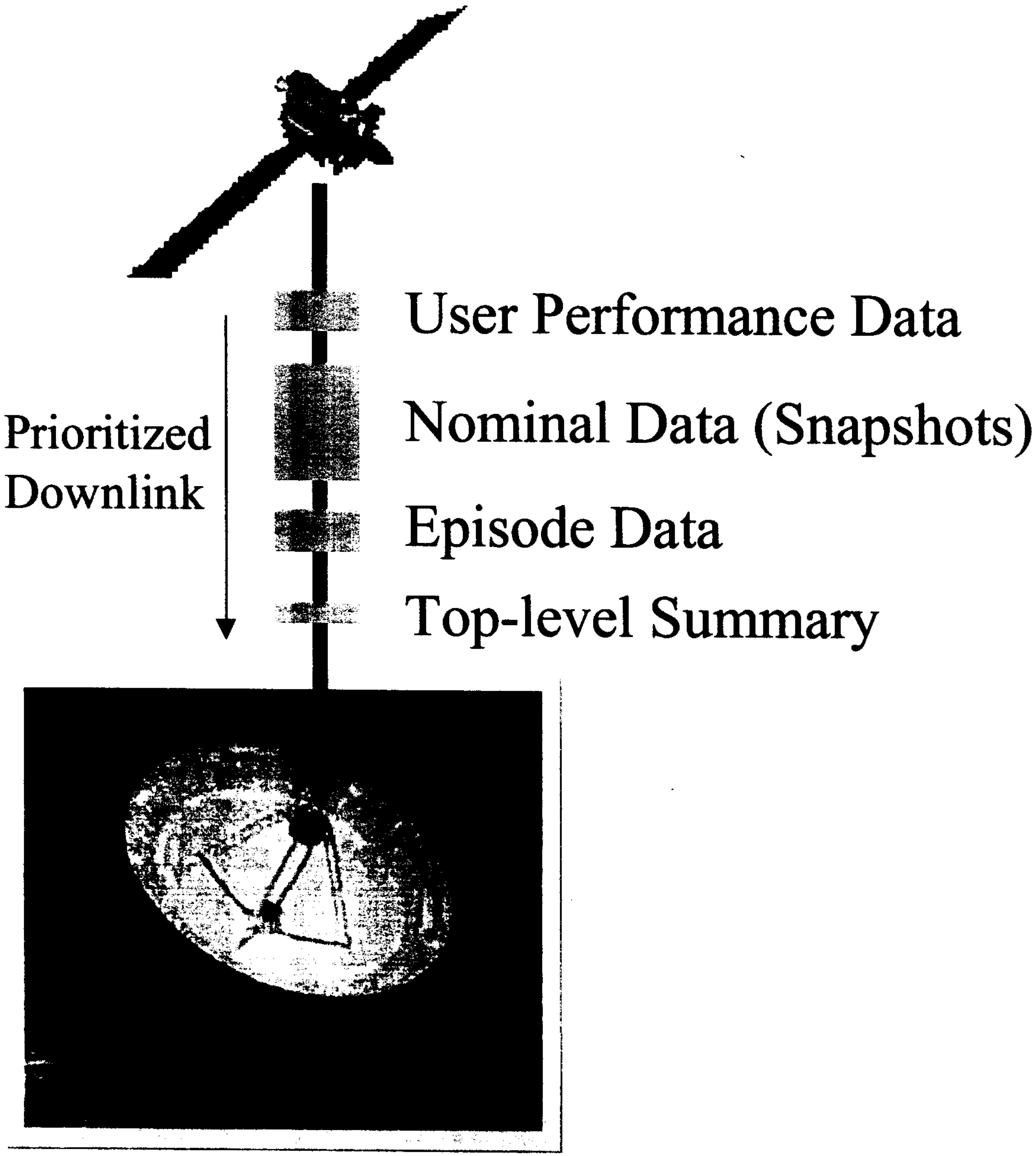
Controller

Schedule, pointing & frequency predicts

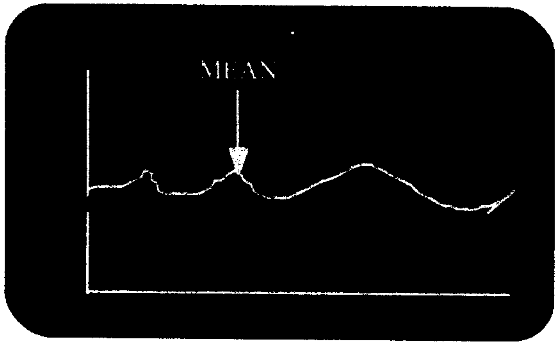
## Detected message & ancillary data

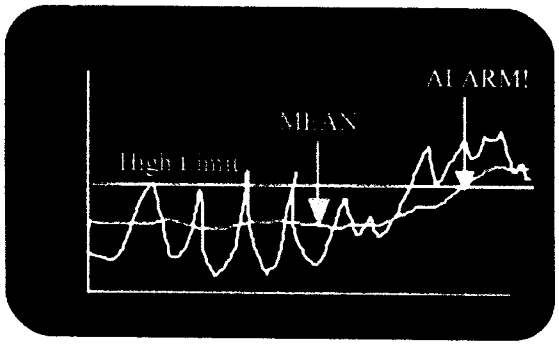


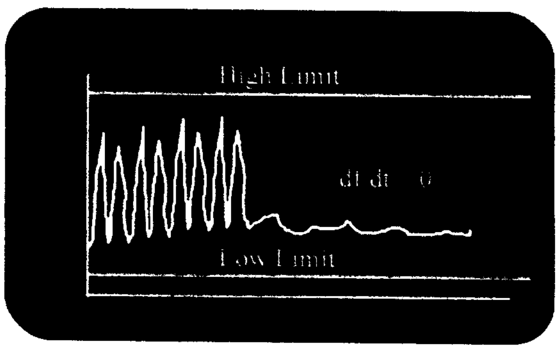
# Summarization: Downlink Products



# Summarization: Transforms



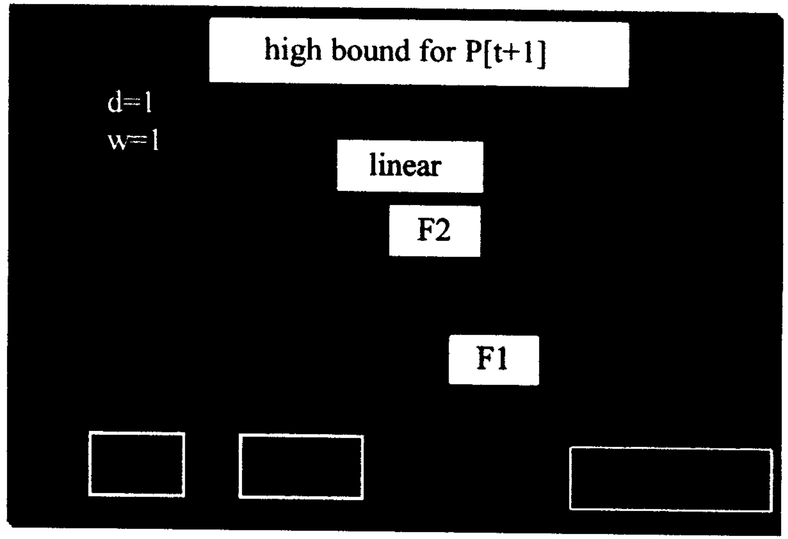



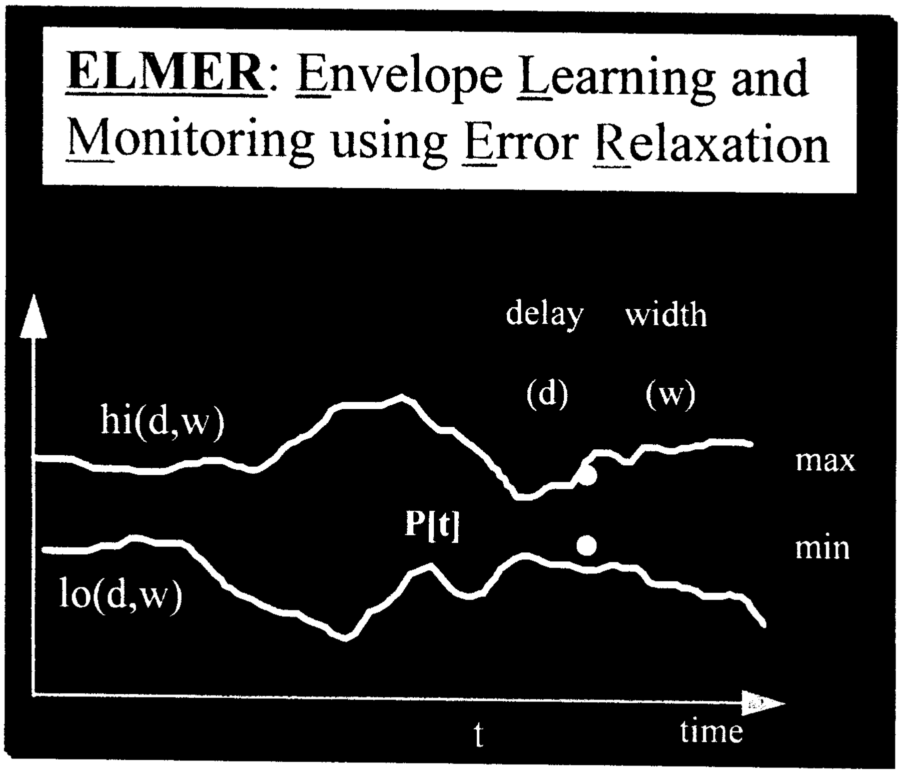




- Transforms currently implemented in DS1 BMOX flight software
  - Maximum and minimum
  - Mean
  - 1st & 2nd Derivative
- Max, Min, Mean are effective at summarizing nominal data
- Transforms can identify Episodes
  - Mean enables detection based on length of time above or below a threshold
  - Derivatives allow detection when an oscillating signal fails to change but is still within the nominal alarm limits (derivatives = 0)
- Transforms can be an input to ELMER adaptive alarm limit technology

# Summarization: ELMER

- ELMER is a concept for replacing hard limits with adaptive (learned) limits
- Major advantages
  - More precise episode identification
  - More accurate anomaly detection
  - Trains on nominal engineering data



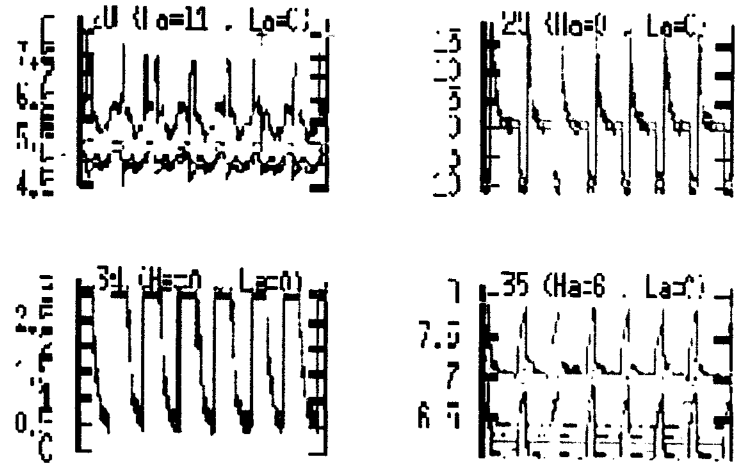

Deep Space One Implementation:

- Can switch between Elmer and traditional limits
- Adaptive limits are not linked to spacecraft fault protection

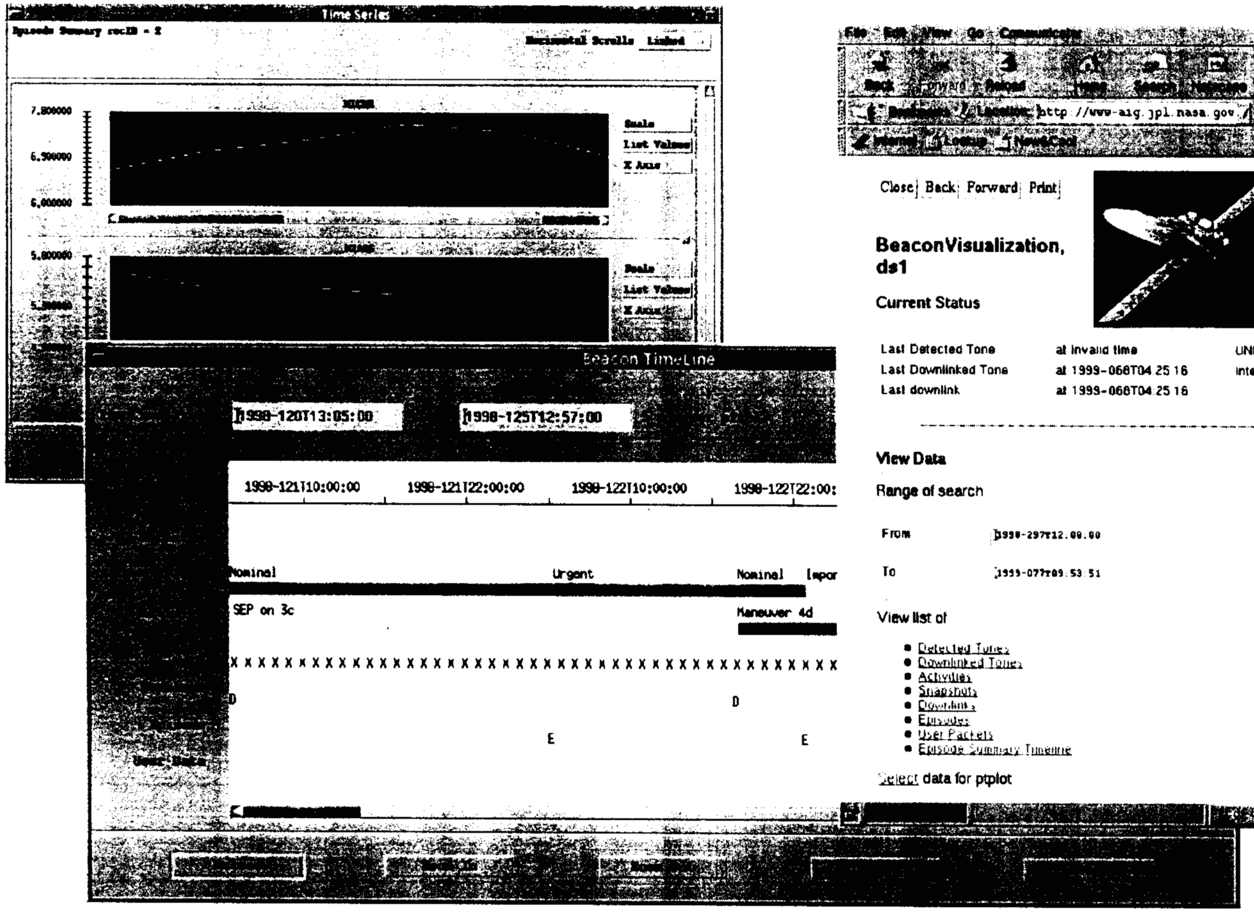
PI: Dr. Dennis Decoste, JPL

# ELMER Technical Approach

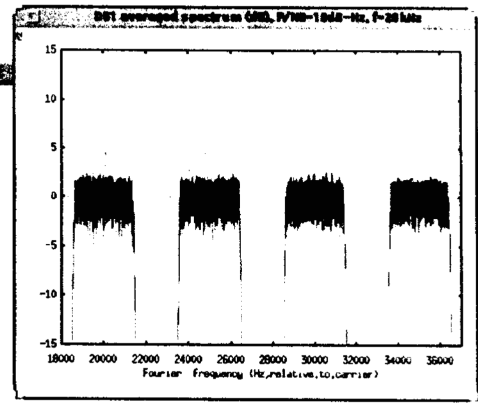
- Technical challenges
  - tasks demand very low false alarm rate (low generalization error)
  - alternatives inadequate (red-lines, error bars, probability density estimation)
- Approach
  - regression w/ asymmetric cost function (looseness cost << alarm cost)
  - form of constrained optimization: minimize (y_i - t_i) subject to y_i >= t_i
- Innovation
  - *bounds estimation* (balance between error bars and PDE; red-lines --> sims)
  - large-scale time-series data-mining
    - (100K features, 10M time points)
- Other challenges
  - input selection
  - inputs probability density (train vs test)
  - constructive/explainable models



# BMOX Ground Software

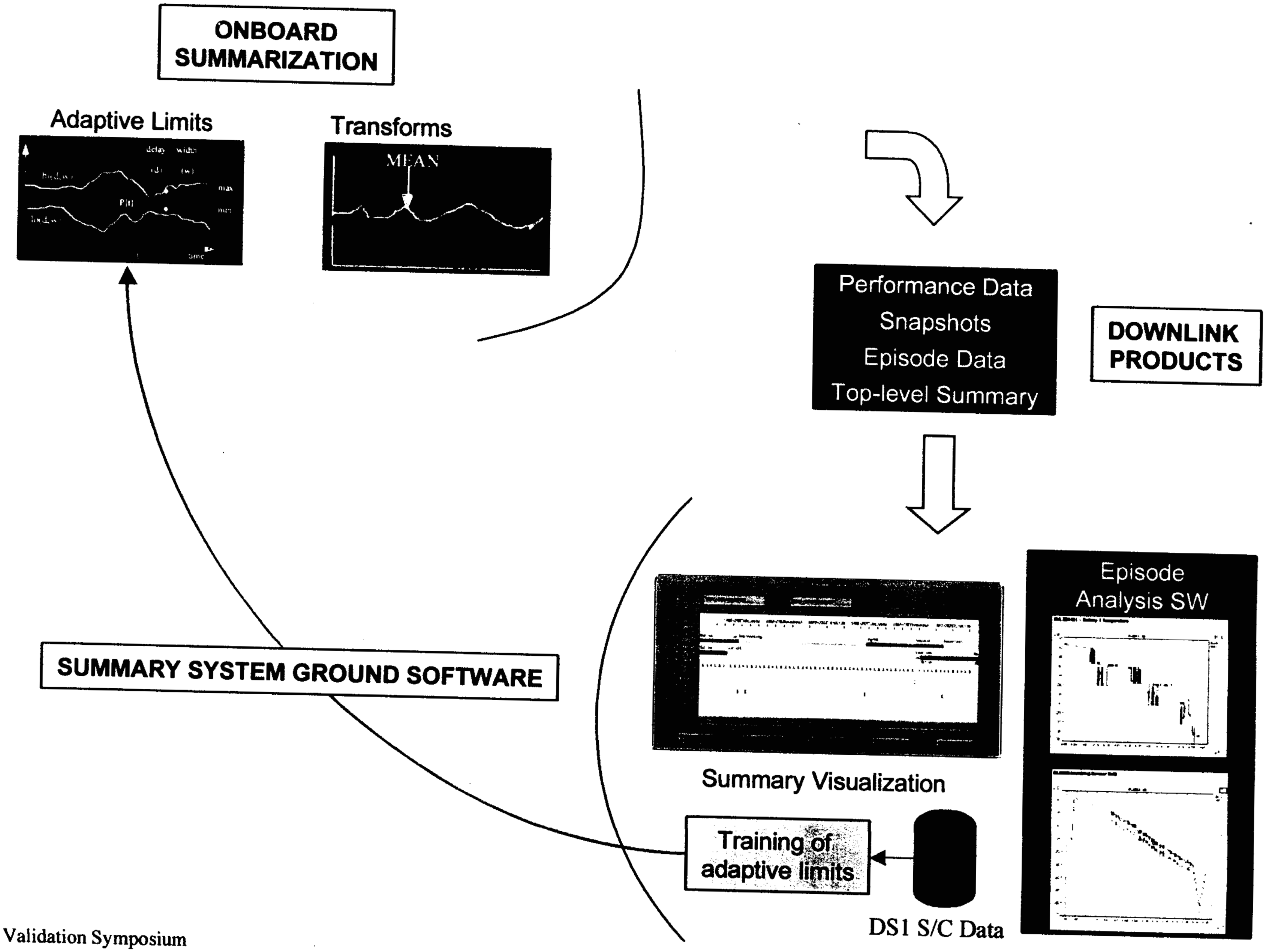



Visualization Tools for Analyzing Summary Data and Tracking Experiment Progress



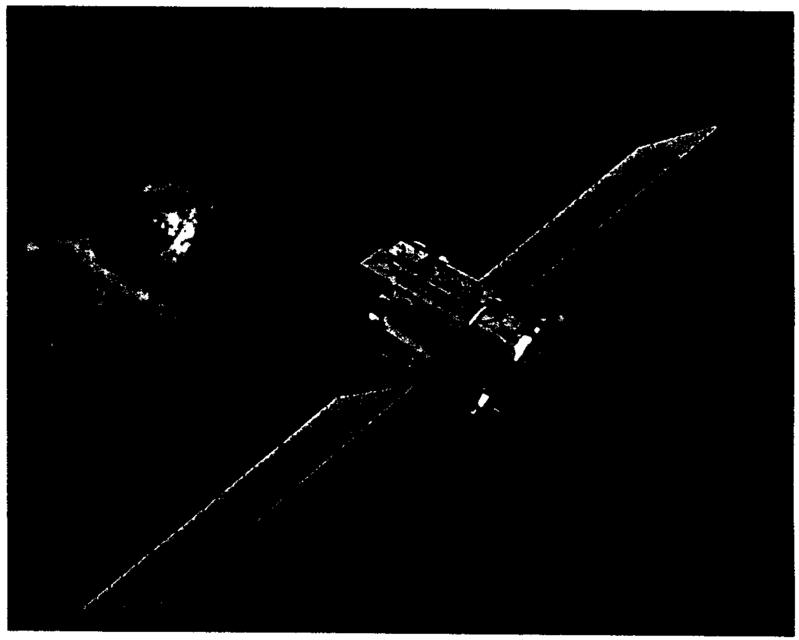

Tone Detection Algorithm

# Summary System Overview



# DS1- Mission Description


- Mission Overview
  - Primary mission objective is to validate high risk technologies
  - Includes an encounter with an asteroid and a possible extended mission to another target body
- BMOX Flight Validation
  - Tone System
  - Summarization System
  - Operational Effectiveness
- Mission Use
  - Tone and summarization systems are available for mission use once validated



# DS1-Experiment Progression

OCT | NOV | DEC | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP

Testing & Updates

Tone Validation

100% Validated

Summary Validation

100% Validated

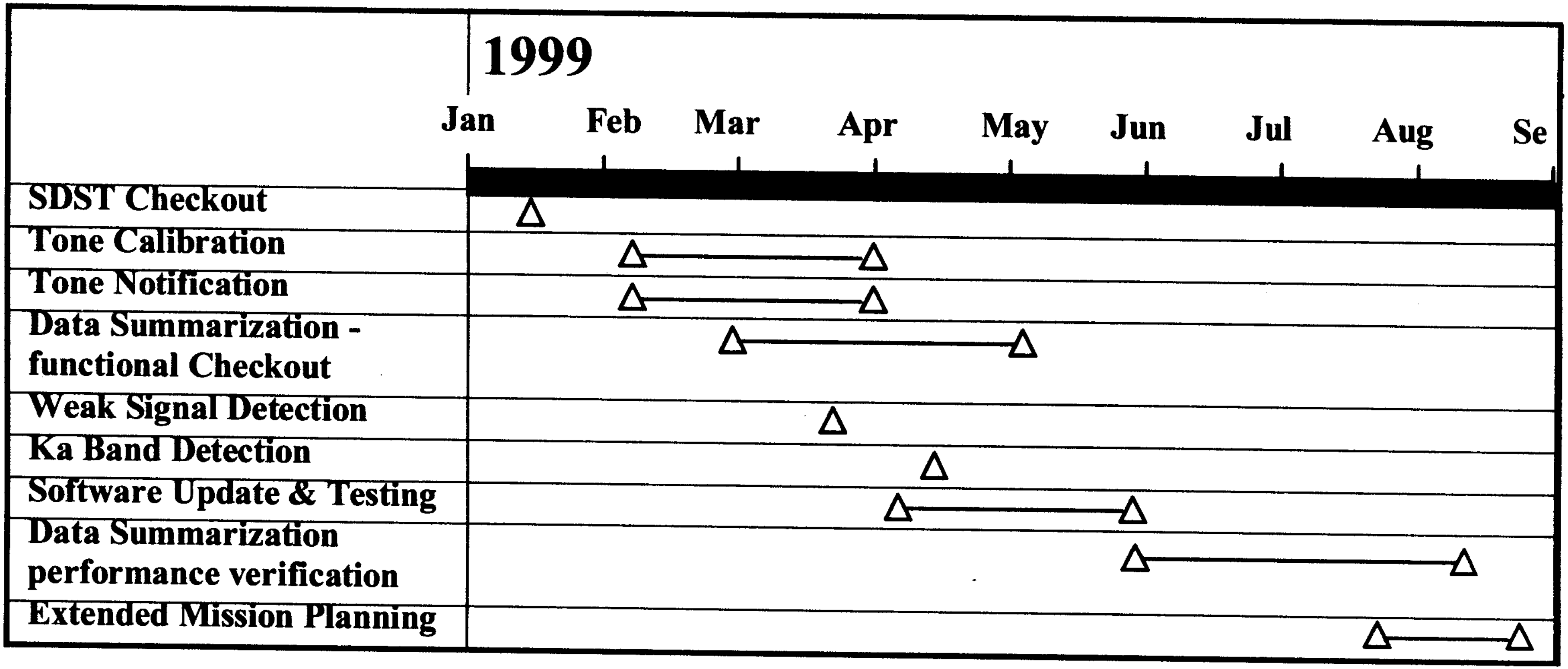
Prepare for Extended Mission

Analyze Results

Experiment Completed

- Validation Status
  - Tone System is 100% Validated (12 experiments conducted)
  - The Summarization System is 100% Validated has been on periodically since to gain additional performance data
  - Operational effectiveness is addressed in the final report
- Follow-on Infusion into DS1 Extended Mission
  - Currently automating tone recording and detection process to make it lower cost
  - Gives the project a way to release-back telemetry tracks that have already been scheduled to lower cost during routine cruise operations
  - Summarization system has been updated and tested periodically

# Detailed Validation Schedule



# Summary of Tone Experiments

| Date | Experiment Type | Results |
|---|---|---|
| Jan. 6 | X-tone, 20, 30, 25, & 35 kHz | Tones found in this order after accounting for 20-second offset in spacecraft internal time. Detection time = 5 min. Frequency offset (FRO) = -4.25kHz, (high gain antenna) |
| Feb. 4 | X-tone, 35 & 20 kHz | Noisy and stable sub-carriers used with low modulation indexes from low gain antenna. All successfully detected. FRO = -1.98kHz |
| Feb. 26 | B-tone & X-tone | Software tone test. All four tones were commanded and transmitted through regular telemetry. |
| Mar. 3 | X-tone, 35 & 20 kHz | Antenna computers down and wind speeds halted antenna several times and early, but several detections were successful at very low levels.<br>FRO=1.25 kHz:<br>20.0001 kHz, DN=3, Pd/N0=8.8, 10 sec,<br>35.0013 kHz, DN=2, Pd/N0=4.2, 15 sec. |
| Mar. 18 | X-tone, 30, 20, 25, & 35 kHz | X-tone successful. After 4.4 kHz carrier offset was found and applied. Spacecraft time found to be 10 seconds later than predicted. IPS was on. |
| Mar. 24 | X-tone | X-tone semi-successful. X-tones found but wrong frequencies because carrier predicts were off by 4.5 kHz and not entered in FSR. |
| Apr. 7 | X-tone, 20, 25, 30, & 30 kHz | X-tone successful. Station needs 45 minutes pre-cal vs. 30. FRO=5.0 kHz. |
| Apr. 1 | B-transmit & X-tone, 20, 25, 30, & 35 kHz | B-transmit successful, 25 kHz tone, needed visibility of carrier before carrier suppression to get correct FRO of 5.5 kHz. X-tone was also successful. |
| Apr. 1 | Ka-tone | The FSR at DSS13 tracked the Ka carrier but the Ka-tone sequence did not get transmitted to the S/C as the auto NAV processing took longer than expected. FRO=0.0 (3-Way). |
| Apr. 2 | B-transmit | B-transmit successful, detection code found 25 kHz tone, needed visibility of carrier to find correct FRO of 6.0 kHz. |
| Apr. 2 | Ka-tone, 20, 25, 30, & 35kHz | Ka-tone was successful for the sequence that was activated. Detection of 20 kHz tone at DN=1 was 4.5 Pd/N0 for 15 sec. FRO=9.9 kHz (wrong up-link freq. in predicts). |
| Apr. 2 | B-transmit | Detection code found 25 kHz tone,<br>FRO of 6.9 kHz was used to center the signal. |

# Validation Details

- Beacon Tone Transmission & Detection
  - Verified that the transponder generates the four beacon tones as instructed via ground command
  - Successfully detected beacon tones to obtain frequency uncertainty estimates
  - Set tone state using flight software

- Engineering Data Summary Generation and Visualization
  - Verified that the flight and ground components of the summary system have been deployed and are functionally checked-out
  - Evaluated software performance and utility to the mission

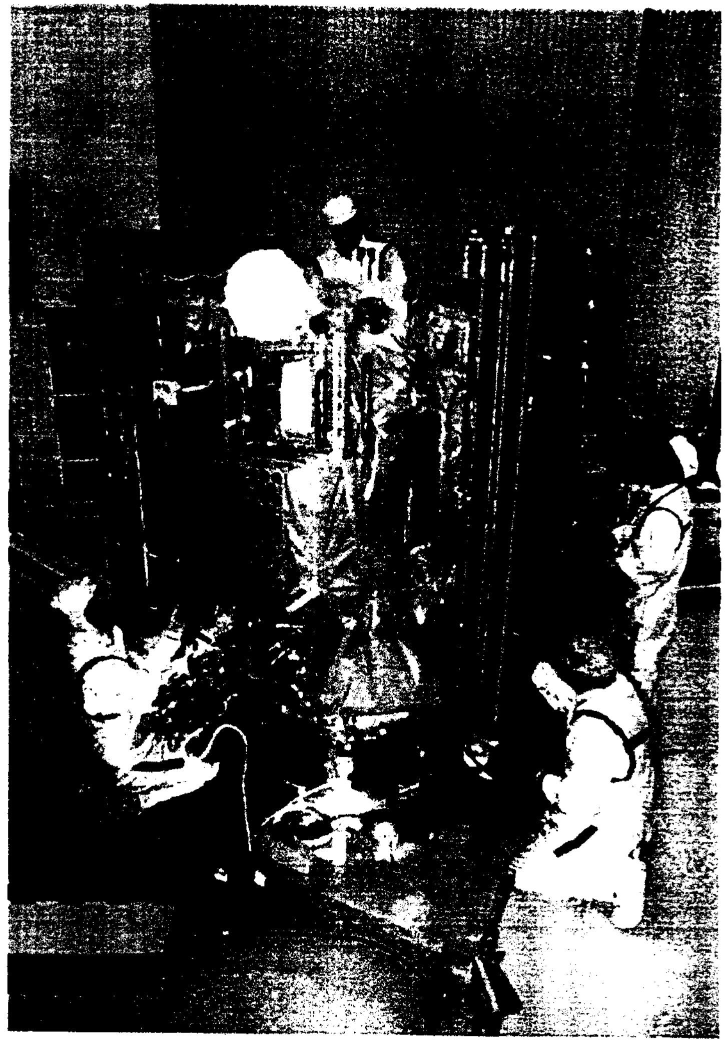
- Tone Message Handling & Reporting
  - Implemented a process for sharing detected tones with DS1 ground personnel and BMOX team members

# Results: Lessons Learned
# Experience from Developing for Flight

- Being part of a flight project resulted in a better technology product
  - tremendous insights into real mission needs resulted in new features that would have otherwise not been implemented
  - insights and experience delivering to flight articles meant the product is more infusible into future missions and technologists are better able to work with missions in the future
  - participation in mission operations enabled evaluation of suitability of this technology to future missions than would have been possible with ground-only standalone demos

# Results: Lessons Learned Software Testing

- The mission development schedule left no time for experiment testing, only essential software
- Late integration resulted in some routine problems that required a new software version to be uploaded in February 1999, delaying validation of the summarization system
- Early testing is essential to prevent problems from occurring after launch!



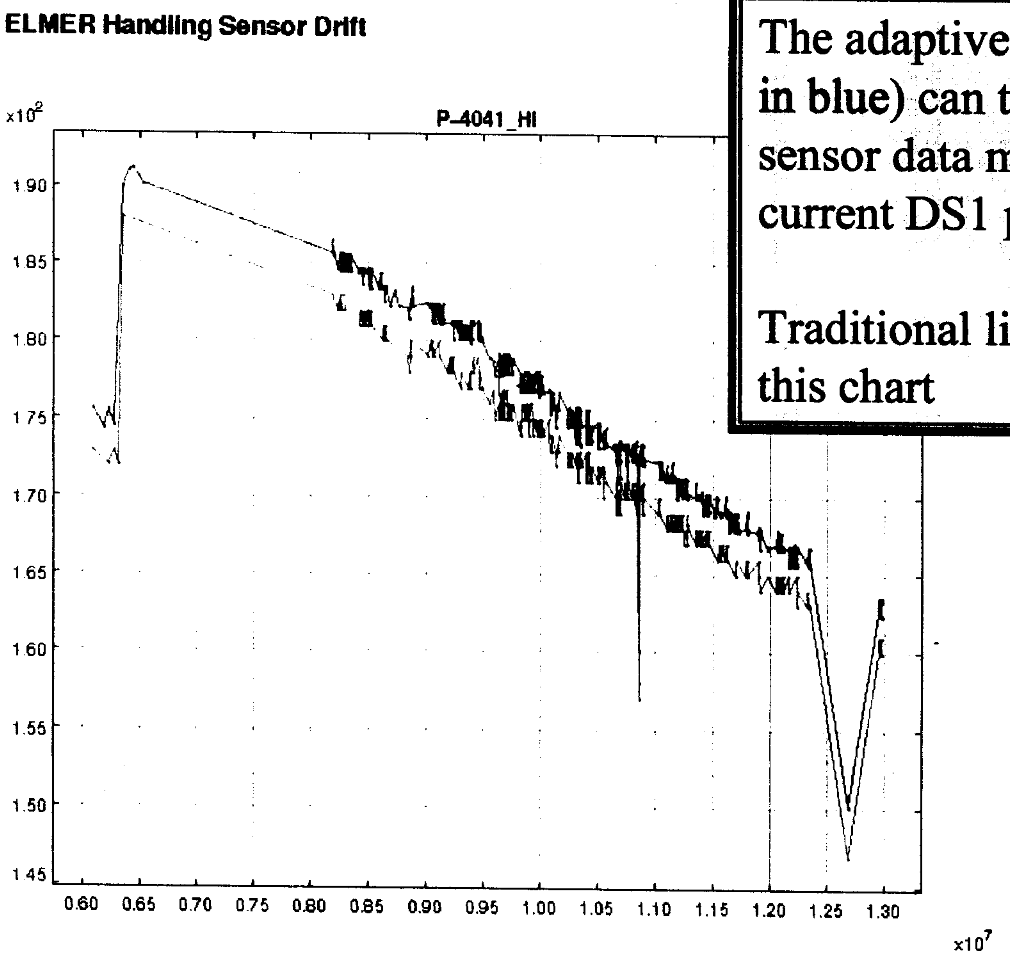
# Results: Lessons Learned
# Fault Protection Integration

- DS1 Beacon tone determination is de-coupled from the DS1 fault protection software

- Future spacecraft should completely integrate fault protection software with the summarization software and beacon tone selection software
  - for better consistency in problem reporting
  - to enable summarization and tone selection to benefit from SOA fault protection designs
  - to enable fault protection to benefit from new anomaly detection methods in the summarization software (adaptive limits,transforms, etc.)

# Results: Summarization SW Performance

81 Days of gradual trending in eight solar array temperature sensors

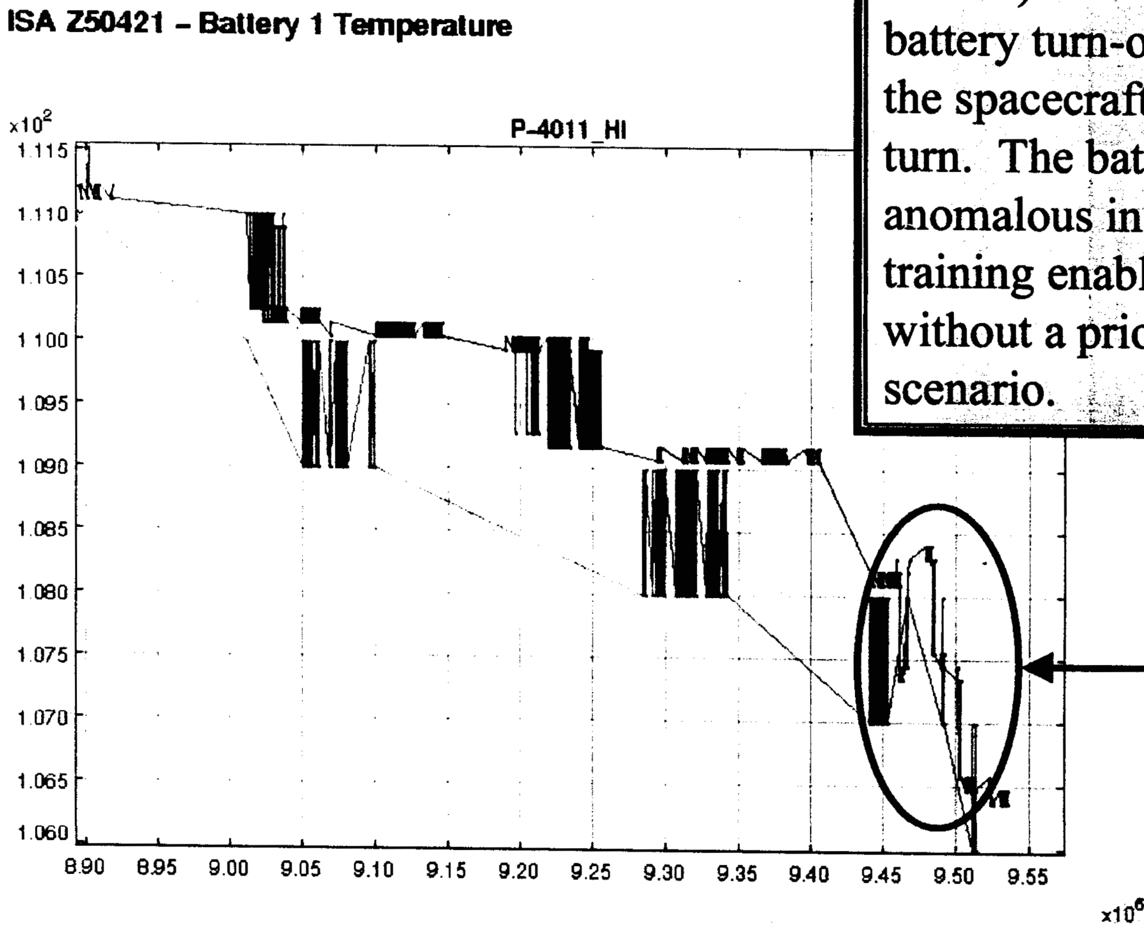



The adaptive alarm threshold (shown in blue) can track gradual trending of sensor data much tighter than the current DS1 project alarm thresholds

Traditional limits are off the scale of this chart

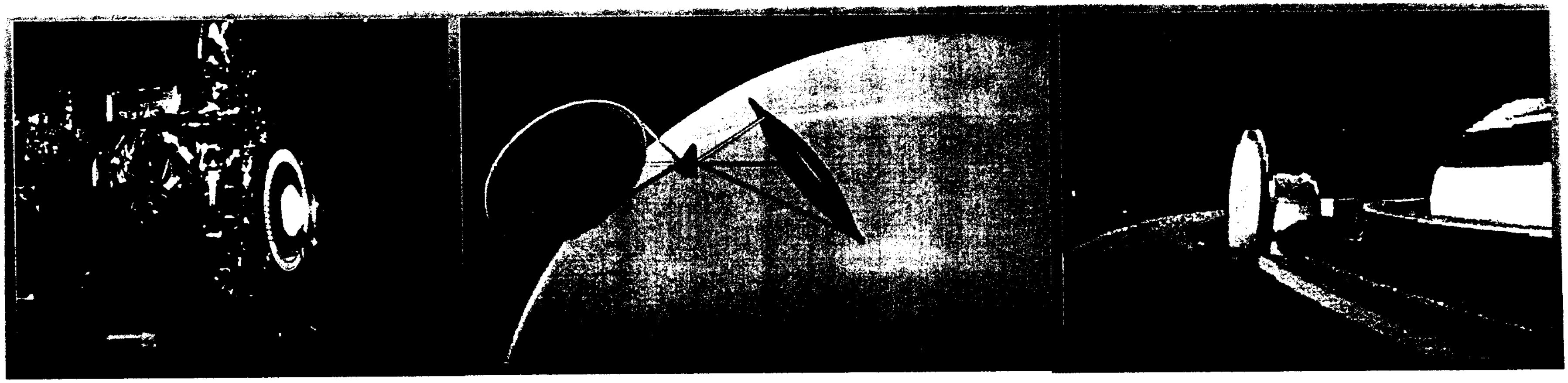
# Results: Summarization SW Performance

Battery turn-on during spacecraft off-axis pointing during a turn on DOY99




The adaptive alarm threshold (shown in blue) shows detection of the battery turn-on that occurred when the spacecraft went off-axis during a turn. The battery turning on was not anomalous in an of itself. ELMER training enabled event detection without a priori knowledge of the scenario.

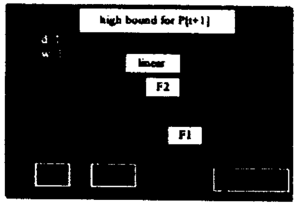
# Results: Applicability to Future Missions



## Reduced Mission Risk for IPS Missions

- IPS provides continuous thrust
- Scaled back telemetry tracking (weekly or less) during cruise periods is being set as a goal whether or not beacon is used.
- A spacecraft anomaly may shut-OFF IPS thrusting resulting in loss of thrust margin until the problem was resolved.
  - Could be up to a week before ground personnel realize that IPS has been disabled
  - With Beacon enabled, response time could be cut to just 1-2 days

# Future Work




Onboard Summarization Research

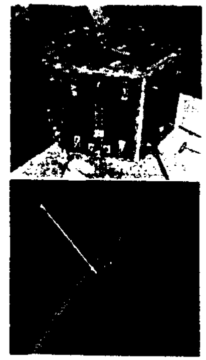
Incorporation of new AI methods
Summarization for long-term archives
[redacted]

Mission Data System

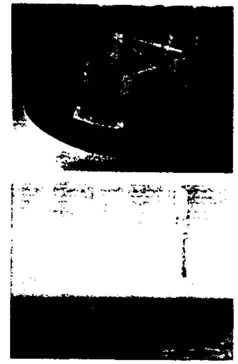
Mission Infusion Path

DS1
Extended
Mission

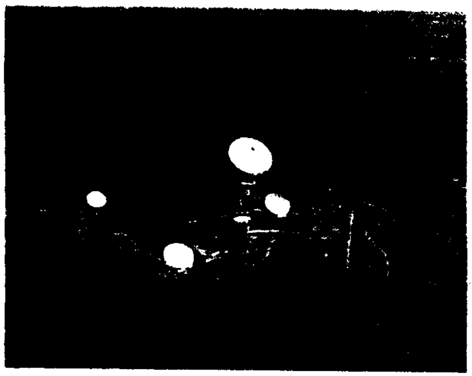
Outer Planets
Missions



Univ. Earth
Orbiters



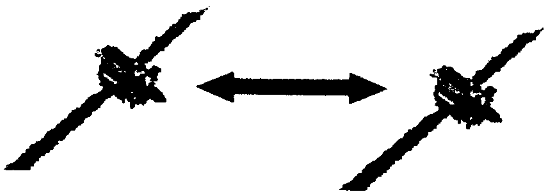
Future
Missions



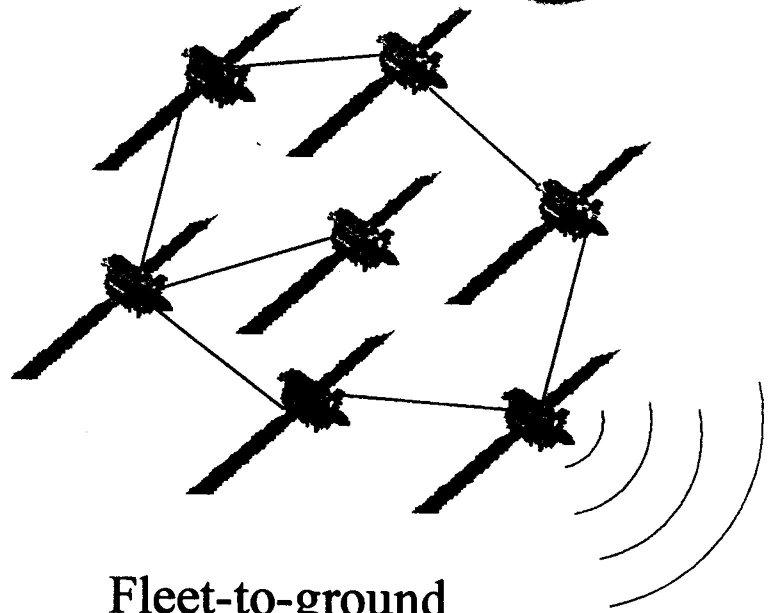
DSN Infusion Path

Standard Beacon Messaging Service
[redacted]

# Future Work: Fleet Summarization



Spacecraft-Spacecraft Summarization



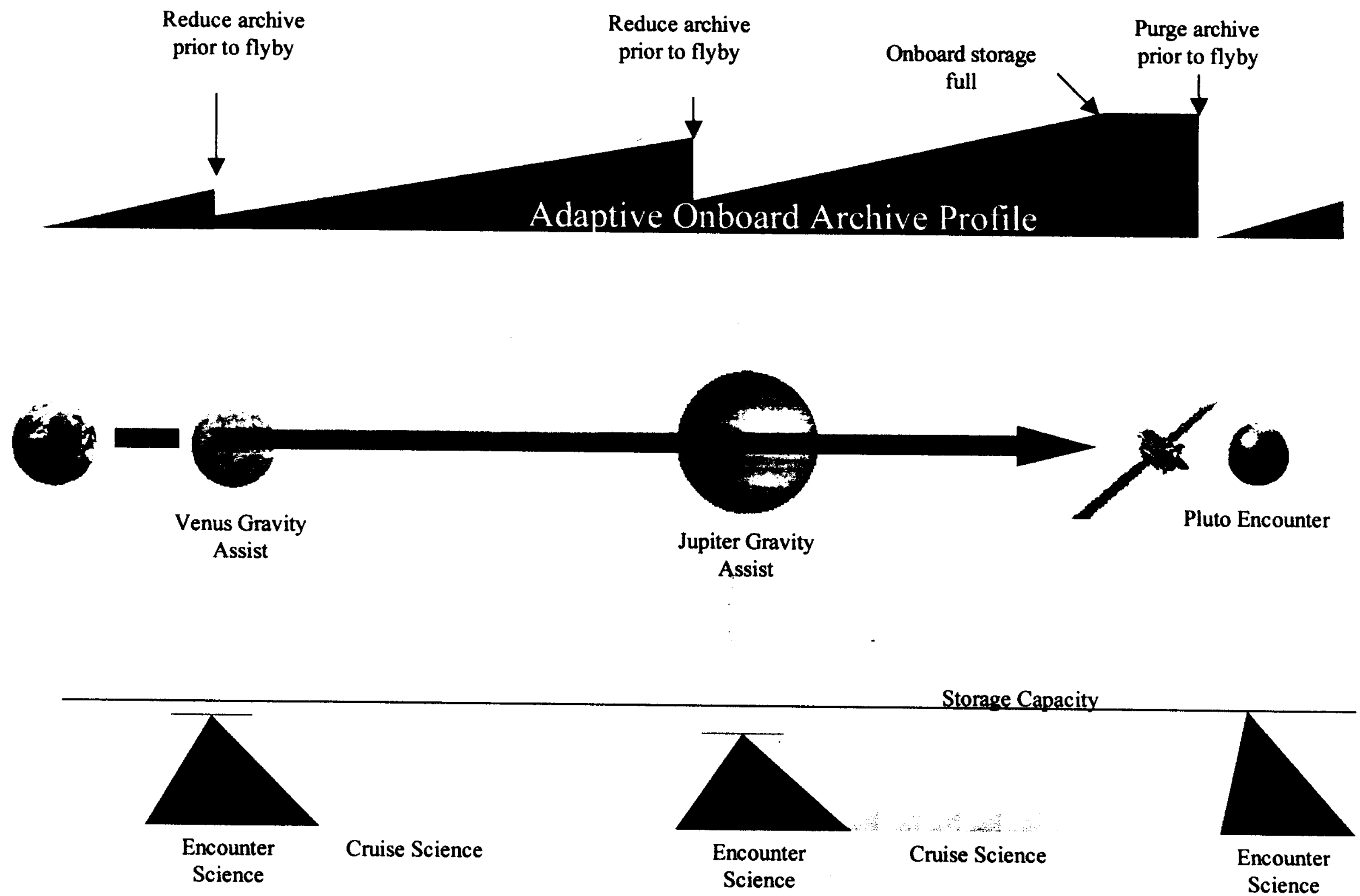
Fleet-to-ground Summarization

Approach

- Transforms, adaptive limits, and episode identification, and other elements of current research can be applied to fleet summarization

- Generation of an operational concept for fleet summarization is complimentary to ongoing efforts in formation flying and fleet infrastructure development.

# Future Work: Archive Data Management

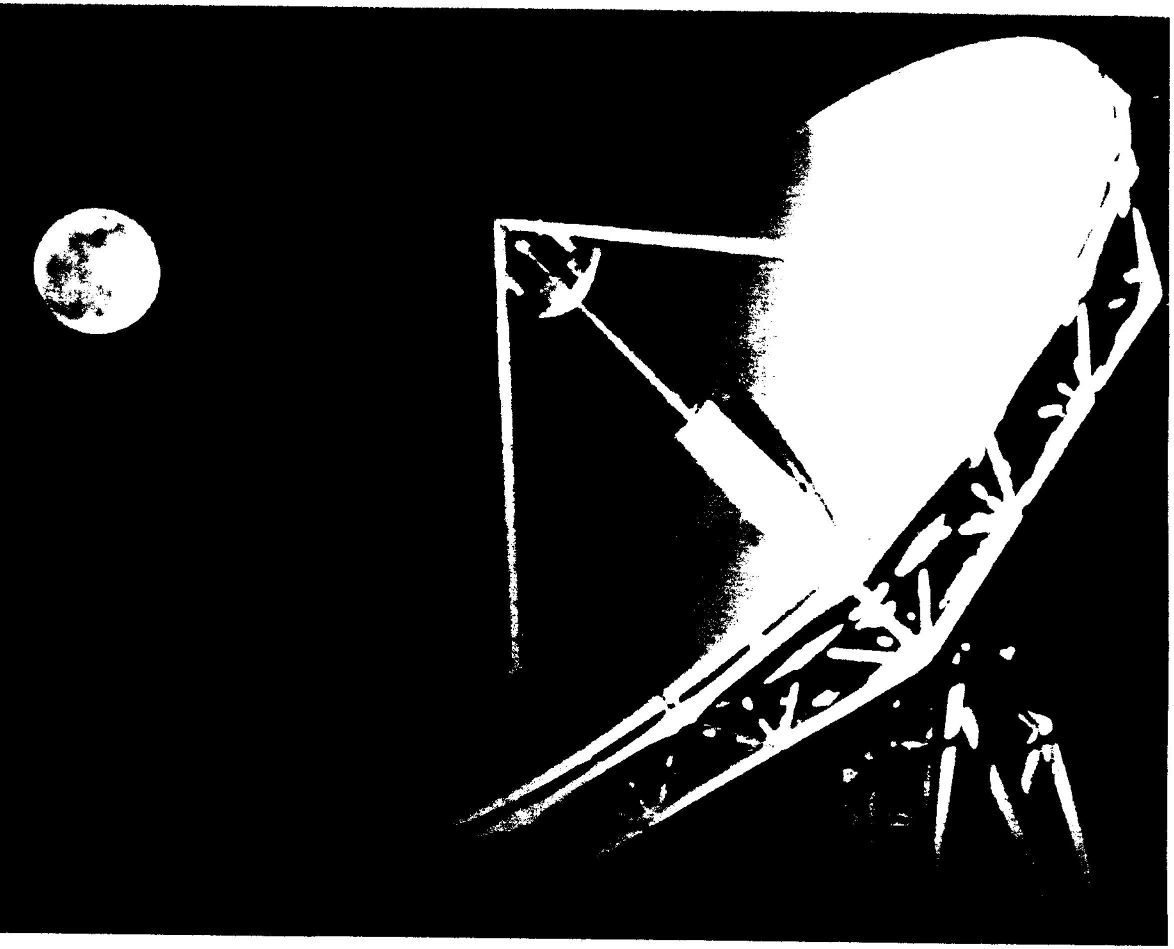


# Acknowledgements

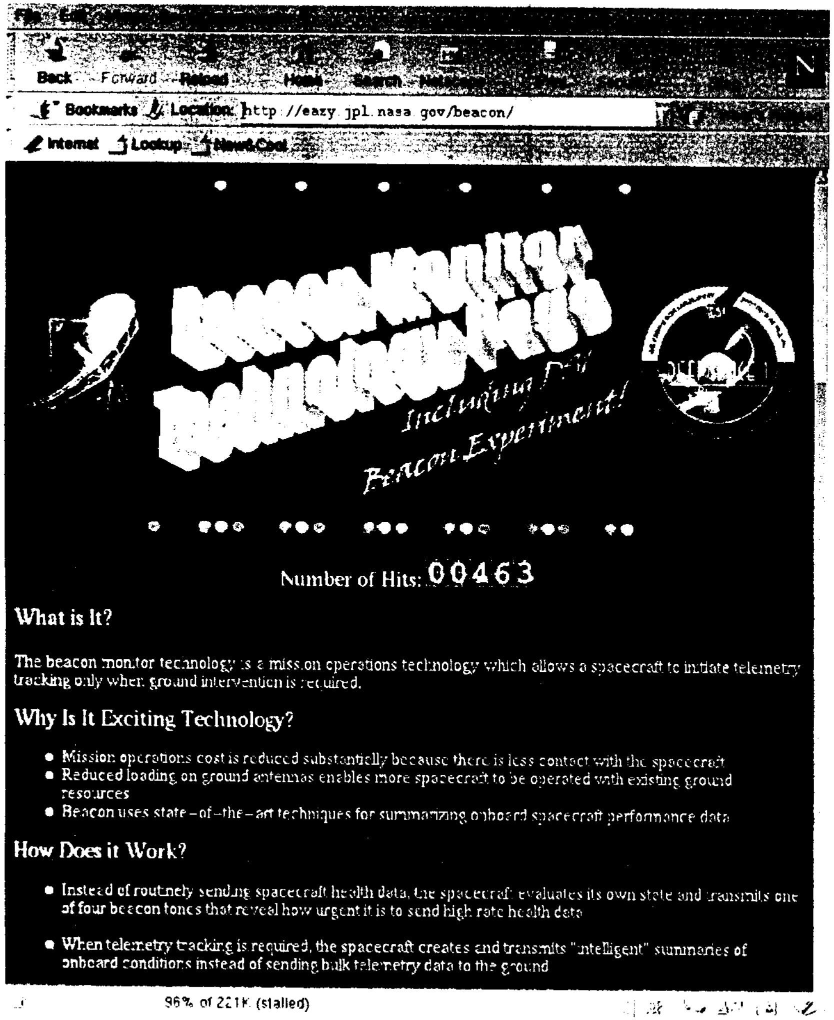
DEEP SPACE 1

## Full DS1 Beacon Monitor Team

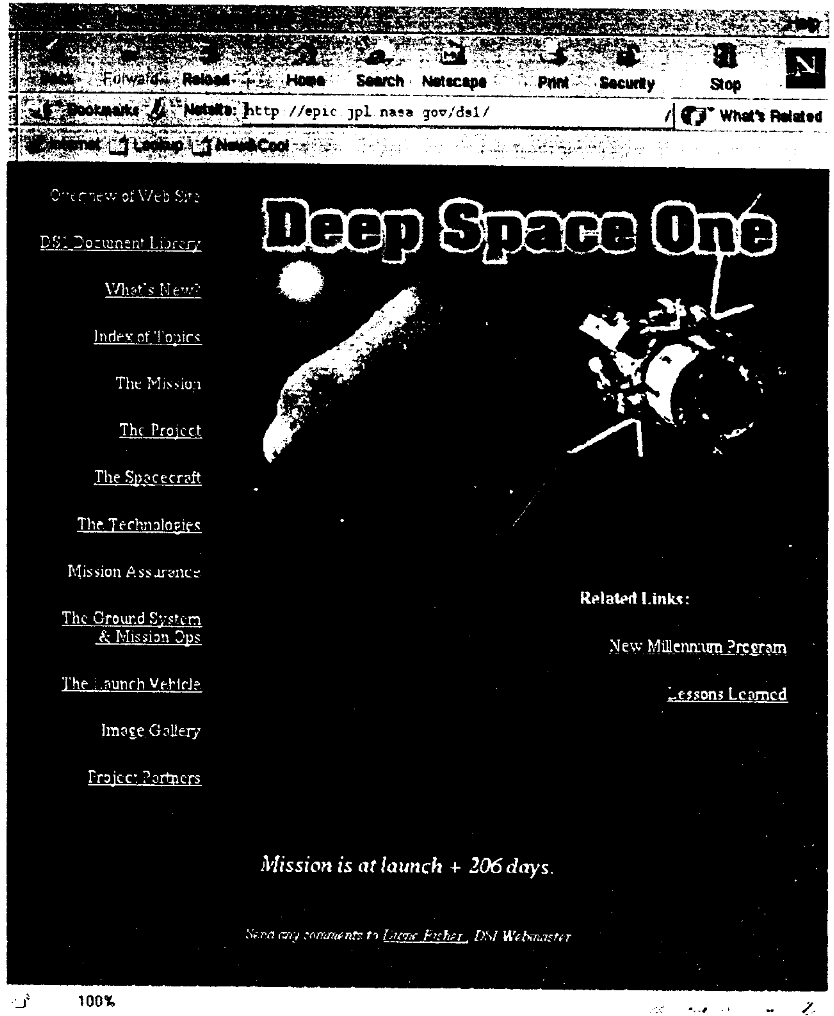
Dennis DeCoste
Sue Finley
Tim Fogarty
Henry Hotz
Gabor Layni
Dave Morabito
Alan Schlutsmeyer
Robert Sherwood
Miles Sue
John Szijjarto
Jim Taylor
Jay Wyatt

# For More Information




**http://eazy.jpl.nasa.gov/beacon**




**http://nmp.jpl.nasa.gov/ds1**

CLEARED